Effect of customization of master gutta-percha cone on apical control of root filling using different techniques: an *ex vivo* study

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Abstract

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Aims (i) To compare the prevalence of extrusion of root filling material when placed using different root filling techniques, with or without customization of the master gutta-percha (GP) cone; and (ii) to investigate the effects of some factors influencing root filling extrusion and presence of voids.

Methodology A total of 180 roots were selected, prepared and randomly allocated to three groups. Five general dental practitioners performed the root fillings; each filled one group of roots ($n = 60$) using each of three techniques; 'cold lateral compaction' ($n = 20$), 'warm vertical compaction' ($n = 20$) and 'continuous-wave' ($n = 20$) techniques. For each obturation technique, the master GP cone was customized using chloroform in 10 samples. Two groups of the roots were recycled to allow all five operators to fulfill their remit. Two observers, blind to operator and obturation technique, examined the radiographs (master apical file, post-obturation) to determine the presence of root filling extrusion and voids within the apical 5 mm, independently. Root filling extrusion was also confirmed by direct inspection of the root apex after obturation. The data were analysed using logistic regression models.

Results A total of 300 root fillings were performed; nine were excluded from the analysis. Most of the root fillings (80%, $n = 233$) were placed within 0.5 mm of the working length; only 20% ($n = 58$) were placed >0.5 mm beyond the working length. The odds of prevalence of extrusion (>0.5 mm) were significantly reduced by about 50% when cold lateral compaction or customization of GP were used. One operator produced 2.5 times more extruded root fillings than others. Curvature & length of root canal, apical size of prepared canal, as well as operator's preferred obturation technique had no significant influence on the prevalence of extrusion. Customization of GP was the sole factor to significantly reduce the prevalence of voids within the apical 5 mm of working length.

Conclusions Root filling extrusion was significantly influenced by 'operator' and was reduced by cold lateral compaction and customization of the master cone. Customization of master cone was the only factor that reduced voids apically.

Keywords: chloroform, customization, obturation, root filling.

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Introduction

Cold lateral compaction of gutta-percha (GP) is still the most commonly used root canal obturation technique in contemporary practice (Jenkins *et al.* 2001, Hommez *et al.* 2003, Bjørndal & Reit 2005). This is despite the recent trend towards the use of warm GP techniques such as warm vertical or continuous-wave compaction of GP, recommended to improve the effective filling of complex root canal systems (Hommez *et al.* 2003). Incomplete obturation of the root canal system and inaccurate apical placement of the final root filling are, nevertheless, common problems for all three techniques

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(Yared *et al.* 1992). The importance of the latter fact lies in the observation that it is the most significant treatment factor influencing the prognosis of root canal treatment (Sjögren *et al.* 1990).

Use of poorly fitting master GP cones is one of the causes of extrusion (Kerezoudis *et al.* 1995). A number of methods of master GP cone selection have been recommended in text books and taught in dental schools including: checking for 'tug back', looking for scratch marks on the cone, taking a cone fit radiograph and placing a feathered cone through the apical foramen followed by trimming of the excess. These approaches do not however take account of the fact that the apical portion of the prepared canal may be irregular in cross-sectional shape (Weine *et al.* 1975).

A modification of the lateral compaction technique involving customization of the apical portion of the master GP cone with chloroform seems to be a logical solution to the problem. Although the use of chloroform-softened master cone during lateral compaction of GP can result in increased microleakage (Zakariasen & Stadem 1982, O'Neill *et al.* 1983), such root fillings have also been reported to appear radiographically more homogeneous in the apical area (Moyer *et al.* 1995), with improved replication of and adaptation to the canal wall (Larder *et al.* 1976, Wong *et al.* 1982, Moyer *et al.* 1995). Interestingly, the control of apical placement of root fillings using this technique has never been reported for any of the three obturation techniques discussed above. The aims of this study were: (i) to compare the prevalence of extrusion of root filling material and voids within the apical 5 mm when placed using different obturation techniques (cold lateral compaction, warm vertical compaction or continuous-wave) with or without customization of the master GP cone; and (ii) to investigate the effects of some factors on the prevalence of root filling extrusion and voids.

Materials and method

Selection of teeth

A total of 180 roots from extracted, human teeth, fulfilling the inclusion criteria: mature apices, absence of unusual morphology, roots with a single canal patent at its apical foramen were selected. They were randomly numbered (1–180) and allocated to three groups, two of which were re-used by different operators: the 1st group of roots was used by operator 1, the 2nd group was used by operators 2 & 3 and the 3rd group was used by operators 4 & 5. Selected roots of multi-rooted teeth were separated by longitudinal sectioning of the tooth. The incisal edge/cusp tip was flattened to provide a reproducible reference point. Each root was then embedded in a custom-made silicone matrix to aid accurate re-positioning for radiographs taken from both bucco-lingual and proximal aspects. All radiographic images of the roots were taken at a fixed distance using a Trophy® X-ray machine (Trophy Radiologie, Rochester, UK), with a 0.4 s exposure at 70 kV and a number two sensor (Schick CDR® Digital Radiography software, Schick technologies, Inc, Long Island City, NY, USA). The object, beam, sensor geometry was standardized using a beam-aiming device (Rinn, Dentsply Ltd, Weybridge, UK).

Canal preparation

Root canal preparation on each root was carried out by one author (SPvZ) after allocation into various groups. After accessing, a size 10 K-Flex file (Kerr UK Ltd, Peterborough, UK) was introduced into the canal of each root to confirm apical patency and the absence of additional canals. Each canal was prepared to 0.5 mm from the apical foramen to a minimum apical size of 30 and .06 taper using NiTi rotary instruments (Profile® & ProTaper®, Dentsply, Maillefer, Ballaigues, Switzerland) and copious amounts of 3.0% sodium hypochlorite (Sainsbury's bleach, J Sainsbury Plc, London, UK) irrigation. The final apical size of the canal preparation was gauged using precurved Flex-O-Files (Dentsply). The curvature of canal in both views was measured based on the radiograph taken with the master apical file at working length using the appropriate functions provided by Schick CDR® Digital Radiography software. The greater degree of curvature of the two measurements taken was used for further analyses.

Obturation

Five general dental practitioners with different dental backgrounds (Table 1) were recruited to carry out the obturation. None of them had been taught or used the technique of customization previously. Prior to the study, they attended a hands-on practical course given by one author (SPvZ) on the techniques involved in this study and had 1 month to practise the techniques on extracted teeth prior to the test. The outcomes were reviewed and appropriate corrective advice was given to achieve a satisfactory standard.

Table 1 Year of qualification, practice type and preferred obturation technique of each operator

Operator	Year of qualification	Type of practice	Preferred obturation technique
Operator 1	1978	Private	Continuous-wave
Operator 2	1983	National Health Service	Cold lateral compaction
Operator 3	1984	Private	Cold lateral compaction
Operator 4	1997	National Health Service	Thermafil®
Operator 5	1999	National Health Service	Thermafil®

Each operator filled one group of the roots ($n = 60$) using each of the three techniques; 'cold lateral compaction' ($n = 20$), 'warm vertical compaction' ($n = 20$) or 'continuous-wave' ($n = 20$). For each technique, the master GP cone was customized using chloroform following a standard protocol in 10 samples. The apices of the roots were masked with tape during obturation. In order to avoid operator fatigue, each operator obturated 60 canals over six 3-h sessions divided into two lots of sessions spaced 7 days apart.

Two groups of the roots were re-used to allow all five operators to use them. The GP was removed using Gates-Glidden drills (Maillefer, Ballaigues, Switzerland) coronally and NiTi rotary instruments (ProTaper®) apically. The residual traces of GP were removed by dissolution with chloroform and wicking with paper points. Radiographic images were taken from both proximal and bucco-lingual aspects to confirm the complete removal of GP. The size of apical preparation, canal curvature and working length were re-determined prior to use by the next operator.

Cold lateral compaction of GP

This was carried out using a standardized master GP cone (Kerr UK Ltd) that fitted snugly at the working length. A thin layer of root canal sealer (Roth Root Canal Sealer, Type 801 Elite Grade, Roth International Ltd, IL, USA) mixed to manufacturer's instructions was introduced into the root canal using a size 15 paper point (ROEKO D-89122, Langenau, Germany). The master cone was coated with a thin film of sealer at the tip, seated and laterally compacted using a finger spreader (Kerr UK Ltd) that could reach the full length of the prepared canal. Additional accessory cones (Kerr UK Ltd) with matching taper were coated with a thin film of sealer, placed into the space created by the spreader and laterally compacted individually using the same finger spreader until the entire canal was filled.

Warm vertical compaction of GP

This was carried out following a protocol adapted from Schilder (1967). Pluggers (Machtou size 1–4, Maillefer Instruments SA, Ballaigues, Switzerland) were used for vertical compaction of GP during down-packing. The pluggers were pre-fitted into the canals using rubber stops (QED, Peterborough, UK) to the following lengths: size 1 plugger reached 5-mm short of the working length without resistance and the pluggers 2–4 reached 7-, 9- and 11-mm short of the working length, respectively. A GP cone of .04 taper (QED) was used as the master cone for down-packing. The apical size of master cone was selected to correspond with the apical size of the prepared canal and fit snugly at the working length. The canal wall was coated with a thin film of root canal sealer using a size 15 paper point and the selected cone was then cemented into place with the tip coated with sealer. Down-packing was completed by thermo-plasticizing the coronal portion of master GP using an electrically heated carrier (Touch & Heat narrow anterior carrier, Analytic Technology, San Diego, CA, USA) and then compacting the heat-softened GP vertically using the pre-measured pluggers. The plugger with the largest diameter was used first and then sequentially smaller pluggers were used as the heated GP mass was moved apically. Apical compaction was deemed complete when the smallest plugger reached 5-mm short of the working length. The coronal portion of the canal was then obturated with thermo-plasticized injectable GP (Obtura II system, Obtura Spartan, Fenton Missouri, MO, USA).

Continuous-wave of GP compaction

This was carried out following a protocol recommended by Buchannan (1996). A plugger (Buchannan pluggers, Analytic technology) that could reach to within 5–7 mm of the canal terminus was selected. This length was marked using a rubber stop at the reference point. A GP cone of .04 taper was used as the master cone for down-packing. The master GP cone was selected and cemented into the canal with sealer, as previously described. The tip of the plugger attached to a System-B heat source (Analytic technology) with the setting at 200± 10 °C and full power mode was placed in the canal orifice beside the master cone and activated. The heated plugger was driven through the GP in a single motion, to a point about 3-mm short of its apical binding point. The plugger was inactivated

whilst apical pressure was maintained and then advanced apically to take up any GP shrinkage during cooling. Following this, the plugger was activated for 1 s again to separate it from the GP mass and remove it. After the removal of excess GP adhering to the walls of the canal, the root canal was back-filled using thermo-plasticized injectable GP (Obtura II system).

Customization of master GP cone

This was carried out following a protocol adapted from Keane & Harrington (1984). Either, a standardized GP cone for the lateral compaction technique or .04 tapered GP cone for the vertical compaction techniques were selected; they were 1–2 sizes larger than the apical preparation and selected to bind at 1-mm short of the working length. The apical 2 mm of the GP cone was dipped in chloroform for 1 s and the softened GP cone was gently placed into a slightly moist canal, noting the orientation of the cone. The GP cone was pushed to the canal terminus in a pumping motion and this was continued for another 10 s to allow the GP to become firm without engaging undercuts. After drying the canal thoroughly and coating with sealer, the customized GP cone was coated with a thin film of sealer and seated following its noted orientation of insertion.

Assessment of obturation

Bucco-lingual and proximal digital radiographic images of the root taken with master apical file at working length and after obturation were assessed by two examiners who were blinded to operator and obturation technique used. They determined the extent of root fillings which were divided into five categories: >0.5-mm short, ≤0.5-mm short, satisfactory, ≤0.5-mm extrusion, >0.5-mm extrusion. GP extrusion was also assessed by inspecting the root apex under 3× magnification after obturation. The presence of voids within the apical 5 mm was also evaluated. The data were analysed using logistic regression models to investigate the influence of some potential prognostic factors on the prevalence of apical extent of root filling or the prevalence of voids.

Results

Apical extent of root filling

A total of 300 root fillings were performed and 291 were included in the analysis. Nine roots were excluded because post-obturation radiographs revealed the presence of a second canal. The analysis for inter-observer agreement revealed substantial agreement (0.76) for measurement of canal curvature, good agreement (0.96) for the assessment of extent of root fillings and moderate agreement (0.45) for the assessment of presence of voids within the apical 5 mm. One way ANOVA and *post hoc* analyses revealed no statistically significant differences in working length, apical size of canal preparation and degree of curvature by either operator or root filling technique.

The distribution of different apical extents of root fillings for each group is summarized in Table 2. Most of the root fillings were placed within 0.5 mm of the working length (80%, $n = 233$); only 20% ($n = 58$) were placed >0.5 mm beyond the working length (only GP extrusion was assessed) (Table 2).

The distribution of those root fillings over-extending by more than 0.5 mm by each of the factors; root filling technique, customization of GP, operator, operator's preferred obturation technique and apical size of preparation is presented in Table 3.

Table 2 Number (%) of cases of different extents of root fillings by different obturation techniques

	Cold lateral compaction		Warm vertical compaction		Continuous-wave		
	No customization (%)	Customization (%)	No customization (%)	Customization (%)	No customization (%)	Customization (%)	Total (%)
Short (≤0.5 mm)	0	2 (4.1)	1 (2.1)	3 (6.1)	0	2 (4.1)	8 (2.7)
Satisfactory*	24 (49.0)	23 (46.9)	16 (34.0)	29 (59.2)	19 (39.6)	19 (38.8)	130 (44.7)
Extrusion (≤0.5 mm)	18 (36.7)	18 (36.7)	14 (29.8)	11 (22.4)	16 (33.3)	18 (36.7)	95 (32.6)
Extrusion (>0.5 mm)	7 (14.3)	6 (12.2)	16 (34.0)	6 (12.2)	13 (27.1)	10 (20.4)	58 (19.9)
Total	49 (100)	49 (100)	47 (100)	49 (100)	48 (100)	49 (100)	291 (100)

NB: None were recorded for the category 'short >0.5 mm.'
*Satisfactory = length of preparation and obturation coincide.

Table 3 The frequency distribution of prevalence of root filling extrusion >0.5 mm for key explanatory variables

Variable	All cases Number	%	Extrusion cases Number	%
Root filling technique				
Cold lateral compaction	98	33.7	13	13.5
Warm vertical compaction	96	32.9	22	22.9
Continuous-wave	97	33.3	23	23.7
Customization of master cone				
Yes	145	49.8	22	15.2
No	146	50.2	36	24.7
Operator				
Operator 1	58	19.9	8	13.8
Operator 2	58	19.9	10	16.9
Operator 3	59	20.3	10	16.9
Operator 4	59	20.3	11	18.6
Operator 5	57	19.6	19	32.2
Operator's preferred technique				
Cold lateral compaction	117	40.2	21	17.8
Continuous-wave	58	19.9	8	13.8
Thermafil®	116	39.9	29	24.6
Apical size of preparation				
30	1	0.3	0	0
35	85	29.2	16	18.8
40	118	40.5	19	16.1
45	47	16.2	11	23.4
50	24	8.2	8	33.3
55	10	3.4	2	20.0
60	3	1.0	0	0
70	3	1.0	2	66.7

The results of single logistic regression analyses for each potential influencing factor (using 'extrusion >0.5 mm' as the dependent variable) are presented in Table 4. The odds of extrusion by more than 0.5 mm were significantly reduced by about 50% when cold lateral compaction ($P = 0.04$, OR = 0.50, 95% CI = 0.26, 0.99) or customization of GP ($P = 0.04$, OR = 0.55, 95% CI = 0.30, 0.99) were used. Operator no. 5 produced 2.5 times more extruded root fillings than other operators ($P = 0.006$, OR = 2.50, 95% CI = 1.31, 4.78). Other factors such as root canal curvature & length, apical size of canal preparation, as well as the operator's preferred obturation technique were shown to have no significant influence on the prevalence of extrusion.

When the three independent variables; 'operator 5', 'cold lateral condensation technique' and 'customization of GP' were analysed simultaneously (Table 5), all the factors remained significant at the 5% level. 'Operator 5' appeared to be the most significant factor influencing the prevalence of root filling extrusion.

Presence of voids within the apical 5 mm of the root filling

Voids within the apical 5 mm were detected on the proximal view (122/290, 42%) more often than on the bucco–lingual view (100/290, 34.5%) but the difference was not statistically significant ($P = 0.073$). The prevalence of voids detected by either view was pooled (148/290, 50.8%) for further analyses and its distribution by obturation technique is summarized in Table 6. The frequency distributions of presence of voids by various potential influencing factors are presented in Table 7.

Table 5 Multiple logistic regression models incorporating combination of several explanatory variables (using extrusion >0.5 mm as the dependent variable)

Explanatory variable (test category/reference category)	Odds ratios	95% CI for OR	*P*-value
Operator (No 5/others)	2.64	1.36, 5.14	0.004*
Cold lateral compaction technique (yes/no)	0.48	0.24, 0.96	0.037*
Customization of GP (yes/no)	0.53	0.24, 0.96	0.036*

**P*-value indicates significance at 5% level.

Table 4 Single logistic regression analyses for each potential explanatory variable using 'extrusion >0.5 mm' as the dependent variable

Explanatory variable (test category/reference category)	Odds ratios	95% CI for OR	*P*-value
Cold lateral compaction technique (yes/no)	0.503	0.257, 0.985	0.045*
Customization of GP (yes/no)	0.547	0.303, 0.986	0.045*
Curvature (Continuous measurement)	0.991	0.955, 1.029	0.630
Apical size of prepared canal (Continuous measurement)	1.039	0.996, 1.084	0.076
Working length (Continuous measurement)	1.047	0.933, 1.174	0.434
Operator's preferred technique (Thermafil®/other techniques)	1.678	0.940, 2.994	0.080
Operator (No 5/others)	2.500	1.306, 4.784	0.006*

**P*-value indicates significance at 5% level.

Table 6 Number (%) of root fillings with voids present within 5 mm from working length by different obturation techniques

	Cold lateral compaction		Warm vertical compaction		Continuous-wave		
	No customization (%)	Customization (%)	No customization (%)	Customization (%)	No customization (%)	Customization (%)	Total (%)
Void absent	20 (40.8)	25 (51.0)	19 (40.4)	33 (67.3)	20 (41.7)	26 (53.1)	143 (49.1)
Voids present	29 (59.2)	24 (49.0)	28 (59.6)	16 (32.7)	28 (58.3)	23 (46.9)	148 (50.9)
Total	49 (100)	49 (100)	47 (100)	49 (100)	48 (100)	49 (100)	291 (100)

Table 7 The frequency distribution of prevalence of voids within the apical 5 mm from working length for key explanatory variables

	All cases		Extrusion cases	
Variable	Number	%	Number	%
Root filling technique				
Cold lateral compaction	98	33.7	53	54.1
Warm vertical compaction	96	32.9	44	45.8
Continuous-wave	97	33.3	51	52.6
Customization of master cone				
Yes	145	49.8	62	42.8
No	146	50.2	86	58.9
Operator				
Operator 1	58	19.9	32	21.6
Operator 2	58	19.9	31	20.9
Operator 3	59	20.3	36	24.3
Operator 4	59	20.3	26	17.6
Operator 5	57	19.6	23	15.5
Operator's preferred technique				
Cold lateral compaction	117	40.2	57	48.7
Continuous-wave	58	19.9	32	55.2
Thermafil®	116	39.9	59	50.9
Apical size of preparation				
30	1	0.3	0	0
35	85	29.2	43	50.6
40	118	40.5	56	47.5
45	47	16.2	28	59.6
50	24	8.2	11	45.8
55	10	3.4	4	40.0
60	3	1.0	3	100
70	3	1.0	3	100

The results of single logistic regression analyses of each potential influencing factor using 'presence of voids within apical 5 mm (on either view)' as the dependent variable are presented in Table 8. Only one factor, 'customization of GP', had significant ($P = 0.006$, OR = 0.52, 95%CI = 0.33, 0.83) influence on the prevalence of voids within the apical 5 mm. The use of customization of master cone could reduce the odds of prevalence of voids by approximately 50%.

Discussion

The length, apical size (gauged by file) and curvature of root canals included in this study were not standardized but recorded and considered as confounding variables in statistical analyses in order to represent various clinical scenarios. The only exclusion criterion was the presence of multiple canals in the same root because the presence of extra canal(s) may complicate the radiographic assessment. The roots were randomly allocated to various operators for different obturation techniques and there was no statistically significant difference in length, apical size and curvature of canal between groups. All root canals in the present study were prepared to a standard taper, 0.06 that would be adequate for all the root filling techniques tested.

Due to the difficulty of obtaining sufficiently large numbers of extracted human teeth, some roots were re-cycled. The concern that the size and shape of the recycled canals may be altered after the removal of GP was recognized and therefore the relevant parameters were re-assessed prior to use by another operator. The re-used roots were *randomly* allocated to the different root filling techniques to be used by the next operator. That any minor changes in root canal anatomy were not of relevance was demonstrated by the fact that there were no statistically significant differences in working length, apical size of canal preparation and degree of curvature by either operator or root filling technique. Furthermore, none of these variables had a significant influence on the extrusion of GP or presence of apical voids.

In this study, only the apical 2 mm of the master GP cone was dipped in chloroform as opposed to the '4–5 mm' recommend by Keane & Harrington (1984). This modification was made based on clinical experience and subjective observations during the laboratory teaching of Endodontic post-graduates. The subjective impression was that the latter protocol resulted in a higher frequency of buckling of the chloroform-softened cone during insertion into canal as well as root filling extrusion. In addition, the present protocol reduces the

Explanatory variable (test category/ reference category)	Odds ratios	59% CI for OR	*P*-value
Customization of GP (yes/no)	0.52	0.33, 0.83	0.006*
Cold lateral compaction technique (yes/no)	1.22	0.75, 1.98	0.434
Warm vertical compaction technique (yes/no)	0.74	0.45, 1.21	0.229
Continuous-wave technique (yes/no)	1.11	0.68, 1.81	0.678
Working length (continuous measurement)	1.09	0.99, 1.20	0.063
Curvature (continuous measurement)	1.02	0.99, 1.05	0.151
Apical size of prepared canal (continuous measurement)	1.03	0.99, 1.07	0.183
Operator 1 (yes/no)	1.24	0.70, 2.21	0.463
Operator 2 (yes/no)	1.14	0.64, 2.03	0.659
Operator 3 (yes/no)	1.68	0.94, 3.01	0.082
Operator 4 (yes/no)	0.71	0.40, 1.26	0.244
Operator 5 (yes/no)	0.59	0.33, 1.06	0.079
Operator prefers cold lateral compaction technique (yes/no)	0.86	0.54, 1.39	0.549
Operator prefers continuous-wave technique (yes/no)	1.24	0.70, 2.21	0.463
Operator prefers Thermafil® (yes/no)	1.00	0.63, 1.60	0.999

Table 8 Single logistic regression analyses of each potential explanatory variable individually using 'presence of voids within the apical 5 mm from working length' as dependent variable

**P* value indicates significance at 5% level.

quantity of chloroform absorbed into and remaining in the master cones, considering the issues of possible toxicity of chloroform. Although chloroform has been banned from sale in some countries because of its toxicity, the Food and Drug Administration in USA has no jurisdiction over a dentist's use of chloroform in clinical practice and has not proven that chloroform is a human carcinogen (McDonald & Vire 1992).

Five general dental practitioners were chosen to take part due to the operator-skill-dependent nature of this study. Each was accustomed to a different obturation technique in clinical practice (Table 1) whilst the techniques under test were learnt or reviewed over a 1 month period, prior to test. The results of their practical exercises on extracted teeth were reviewed regularly by SPvZ and any mistakes were pointed out and corrected in order to ensure all the practitioners were familiar with each technique.

Acquisition of skills to master a technique is not a mere matter of following prescribed protocol but of acquiring tactile sense by a process yet undefined (Gulabivala *et al.* 2000). Interestingly, 'operator' did emerge as the most significant factor affecting the prevalence of root filling extrusion although it did not influence the prevalence of voids in the root fillings. Operator 5, who produced the highest number of extruded root fillings, was the least experienced amongst the operators and favoured Thermafil® for obturation in their practice. Possibly, the ability to control accurate placement of root filling requires specific tactile skills that were, as yet, poorly developed by operator 5, and furthermore, that the skills required for achieving a dense root filling may be different.

For the statistical analysis in this study, only GP extrusion was considered as root filling extrusion. Initially, the apical extent of root filling was assessed by both visual inspection of the apex for GP extrusion and comparison of working length and post-obturation radiographic images. It was found that only a very small proportion of roots had short root fillings (8/291, 2.7%), all of which were ≤0.5-mm short of the working length. Amongst the over-extended root fillings (153/291, 52.5%), the majority (95/153, 62%) were ≤0.5 mm beyond the working length. Considering the probable measuring error during working length determination, root canal preparation and obturation, the categories '≤0.5-mm short' ($n = 8$), 'satisfactory' ($n = 130$) and '≤0.5-mm extrusion beyond working length' ($n = 95$) were classified as 'no extrusion' for the logistic regression analyses. Whereas, those judged as '>0.5-mm extrusion of GP beyond the working length' ($n = 58$) were classified as 'presence of extrusion'. This figure corresponded to the prevalence of extrusions detected by visual inspection of the root apex after obturation.

In general, this study showed a low prevalence of short root fillings (2.7%) compared with the high prevalence (38–58%) reported in previous epidemiological studies (Bergström *et al.* 1987, Odesjö *et al.* 1990, Eckerböm *et al.* 1991, De Cleen *et al.* 1993, Buckley & Spångberg 1995, Saunders *et al.* 1997). As the apical extent of root filling is directly affected by the

apical extent and taper of root canal preparation, the above discrepancy might be attributed to the fact that all the canals were prepared to a standard taper and were patent at the foramen. In addition, the operators in this study knew that their specimens would be analysed by the investigators, whilst the operators who have performed root canal fillings in teeth that are included in epidemiological studies have no idea at the time of treatment that their work would be assessed as part of a study and therefore they may not be as critical in their performance. On the other hand, the prevalence of voids within the apical 5 mm of the working length was high (50.9%) and in agreement with previous epidemiology studies (Bergström *et al.* 1987, Eckerböm *et al.* 1989).

Apart from 'operator', two other factors, 'cold lateral compaction technique' and 'customization of GP', also had significant effects on the prevalence of root filling extrusion. The use of the cold lateral compaction technique produced significantly less extrusion than the two vertical compaction techniques, consistent with clinical experience and research (Yared *et al.* 1992).

The use of master cone customization was the only factor that significantly reduced the prevalence of voids in the apical 5 mm of working length. This is in agreement with Keane & Harrington (1984) who reported that cold lateral compaction with the master cone modified by chloroform produced a dense, homogenous filling in the apical one-third. This technique has not been tested when used in combination with intra-canal thermoplastized GP obturation techniques.

Based on this study, chloroform customization of the master GP cone is recommended, especially when using the warm vertical compaction technique or the continuous-wave compaction technique as tested in this study.

Root canal preparation requires unique tactile skills and this requirement also extends to obturation techniques. This variable should be accounted for both in future research on obturation techniques as well as teaching them to novices.

Conclusions

'Operator' emerged as the most significant factor affecting the prevalence of root filling extrusion. The prevalence of root filling extrusion was also significantly lower when cold lateral compaction and customization of the master GP cone were used. Customization of master GP cone was the only factor affecting the prevalence of voids.

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